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Indian J. Phys. **67A** (3), 293-296 (1993)

The conductivity and fluid flow permeability of porous fired clay

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Received 7 April 1992, accepted 15 February 1993

Abstract : The electrical conductivity of salt water-saturated porous fired clay has been measured. The results showed an Archie's law behaviour $\sigma_c = a\sigma_w \Phi^m$, where ($\Phi$) is the porosity of the sample, (σ_c) and (σ_w) are the conductivities of the saturated sample and water respectively. The exponent (m) was fund to be 1.96. The fluid flow permeability (K_r) was also measured for these samples and found to be proportional to $\Phi^{m'}$ with m' =3.84 which is consistent with the well known Kozeny equation. The relation between (m) and (m') is in a good agreement with the theoretical value $m' = 2m$.

Keywords : Electrical conductivity, fired clay, fluid flow permeability .

PACS Nos. : 47.55.Mh, 72.80.–r

The dc electrical conductivity of a large number of brine saturated samples, taken from a wide variety of sand formation, was measured by Archie [1]. As a result, he proposed an empirical equation relating the electrical conductivity of the formation completely saturated with water (σ_c) to the porosity of the formation (Φ) :

$$\sigma_c/\sigma_w = 1/F = a\Phi^m \tag{1}$$

where (σ_w) is the water conductivity, (F) is the formation factor, (Φ) is the porosity, (a) and (m) are empirical parameters that vary with the sample microgeometry. The above equation is known afterwards by Archie's law which uptil now has no theoretical foundation.

Basing on the experimental measurements, the parameter (a) is generally assumed to be constant equal to 1.00, while (m) is found to vary within a range from 1.50 to 4.00. Eq. (1) was reconfirmed by numerous investigators [2–4].

The "iterated dilute limit model" is a recent.theoretical model proposed by Sen *et al* [5], for a system of spheres embedded in a homogeneous media for $\Phi \geq 0.6$, giving 1.50 as a value for (m).

For fluid permeability, there is another empirical law known as Kozeny equation [6] which relates the permeability (K_r) to the porosity (Φ). Wong *et al* [7] suggested a modified form for the Kozeny equation which relates the fluid flow permeability to the formation factor (F) defined in eq. (1). This is :

$$K_r \propto F^{-2} \tag{2}$$

which is equivalent to :

$$K_r \propto \Phi^{m'} \tag{3}$$

with $m' = 2m$.

In the present work, the relation between the conductivity and the fluid flow permeability for porous fired Egyptian clay was investigated to test the findings of Wong *et al* [7] concerning the values of the exponents (m) and (m').

A very fine powder of particle size less than 100 μm of Egyptain clay (the trade name is "tafla") produced at Abu-Siebera, Aswan, was brought from the Egyptian Company for Refractories. The powder was dried for 3 hours at 100°C, sieved and pressed in the form of discs of diameter 2.5 cm and average thickness 3 mm. A very large number of samples were prepared using different pressures in order to obtain a wide range of porosities. The samples were fired at 1200°C for 6 hours. The porosity of each samples was determined by measuring the true density of the solid material (fired clay) and the apparent density of the sample (fired pressed discs). The fluid flow permeability (K_r) was measured for ten samples of porosities ranging from 0.22 to 0.44 by the use of a simple arrangement to change the falling water head over the sample. The flow rates of distilled water through every sample, at five different pressure gradients across it, were determined by measuring the volume of the water passed through the sample in a certain time. A linear least square fit of the pressure gradients ($\Delta P/d$) and the corresponding flow rates (Q) gives a slope from which (K_r) can be determined using the equation :

$$Q/(\Delta P/d) = K_r A/\eta \tag{4}$$

where (d) and (A) are the thickness and cross sectional area of the sample, (η) is the viscosity of the distilled water at the temperature of the experiment.

For measuring the electrical conductivity, another group of samples, of the same porosities as the first group for the permeability measurements, are used. Each sample was placed in a vacuum chamber to remove the air from its pore spaces, then a salt water of salinity 1% by weight was allowed to enter into the evacuated chamber to fill the pores. The electrical conductivity of the salt water (σ_w) was measured by Hanna Conductivity Meter Type HI 8633 and found to be 1.45 $\text{ohm}^{-1}\text{m}^{-1}$. The elctrical conductivity of each saturated sample (σ_c) was measured using Tesla Impedance Meter Type BM507. The formation factor (F) for each sample was then calculated from the definition

$$F = \sigma_w/\sigma_c .$$

A linear fitting for ($\log \sigma_c$) versus ($\log \Phi$) is shown in Figure 1. From the slope of the straight line and the intercept, the exponent (m) and the constant (a) were found to be

1.96 and 1.11 respectively, giving an indication that Archie's law given in eq. (1) is applicable for the present conditions.

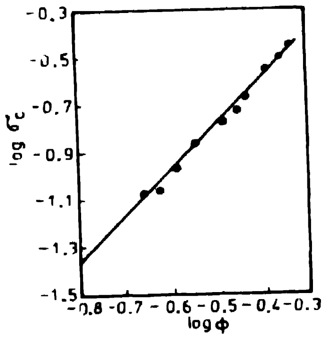

Figure 1. Variation of the conductivity of the salt water-saturated samples as a function of porosity.

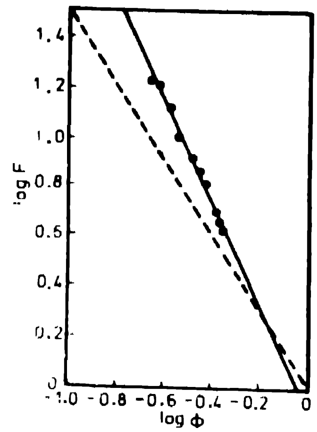

Figure 2. The formation factor as a function of porosity. The dashed line is the prediction of the self-similar model, ref. [5].

The values of (F) calculated from the present work are plotted against (Φ) on a logarithmic scales compared with those of the "iterated limit" theoretical model (solid and dashed lines respectively), Figure 2. The comparison of the values of (a) and (m) shows a disagreement between the present work and the theoretical model of Sen *et al* [5]. This disagreement is attributed to the fact that the exponent (m) is a shape function. This function increases as the grain shape deviates from the spherical shape, this is the case in the clay particles which are not completely spherical but have some of plate-like structures. The present results are in a good agreement with the work of Jackson *et al* [4] and Brouers and Ramsamugh [8].

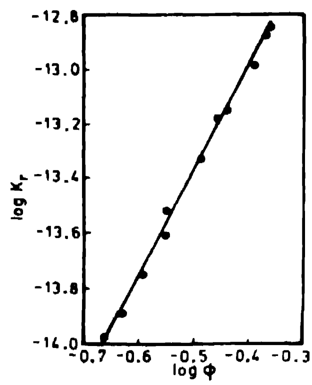

Figure 3. Variation of the permeability as a function of the porosity.

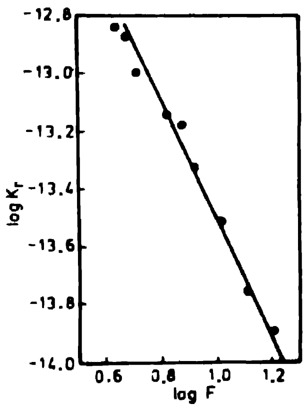

Figure 4. Variation of the permeability as a function of the formation factor.

When the values of (log K_r) are plotted *versus* (log Φ) as shown in Figure 3, the slope of the resulting straight line was found to be 3.84. This means that :

$$K_r \propto \Phi^{3.84} \tag{5}$$

The linear fitting of (log K_r) *versus* (log F) as shown in Figure 4 gave a slope equal to −2.02 which leads approximately to :

$$K_r \propto F^{-2} \tag{6}$$

This is a good support to the theoretical prediction of Wong *et al* [7] who suggested the same relation between the fluid flow permeability (K_r) and the formation factor (F).

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